Ambient Air Safety Aware Autonomous Evacuation Algorithm

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Abstract:- **Dijkstra's Algorithm (Open Shortest Path) is widely used in evacuation algorithm by considering the heuristic estimated least cost between possible path, to compute the choicest path from a hazard. However, these calculated shortest path solutions lack safety intelligence and can usher evacuees into the shortest path to danger. This project designs and implements a Dijkstra based algorithm by implementing real time ambient air quality data to enforce Safe and Autonomous Evacuations using intelligent signage reinforcement. Improving on Dijkstra's algorithm, our cloud-based system is deployed to send real time updates and alerts of indoor environmental-CO levels. MQ-7 sensor readings are used to establish Air Quality Index (AQI) for LED signage before broadcasting on the mobile cloud of stakeholders using Message Queuing Telemetry Transport (MQTT) protocol. All communication between IoT devices and end-users is instantiated by the deployed Esp8266 Wi-Fi module (broker). MQTT protocol publishes and subscribes messages between the IoT 'things' according to their roles in the designing of the system. Transport layer security (TLS) Protocol secures the data in transit between the ground-based sensors and the cloud-based Thingspeak server. Deployed MQ7 sensors on Arduino Nano development board. ESP8266 collaborates all communication between components via the NodeMCU-12E broker. A safety function is used within Dijkstra's algorithm. Instead of applying a time cost, we use a safety heuristic to computes the safest path from any given starting point to a safe destination evacuation point. Signages within the building implements the safety awareness using signage based on Air Quality Index (AQI) data as well as via the directed evacuation path graph on a mobile application. Safe route is also broadcast to all stakeholders within the Android application's mobile cloud.**

Keywords— ***Wi-Fi, Carbon monoxide, Sensor node, Vertices, Internet of Things, Algorithm, Evacuation.***

I. INTRODUCTION

In 1959, Dr Edsger Dijkstra designed a classically efficient algorithm for computing the shortest or quickest path from a single point (vertex) to multiple vertices. Dijkstra's algorithm is basically a greed algorithm implementation which in this case can be used to work out the fastest way out of danger. It picks up the path of the least cost when faced by a decision on path selection. If we can measure safety levels along edges, only then can we effectively and practically utilize Dijkstra's algorithm to determine optimal safety evacuation paths from a source point to any destination or exit.

When fire hazards happen, seemingly familiar indoor environments rapidly and dynamically change into unfamiliar environments rendering usually calculated shortest paths into possibly unsafe paths. Evacuation algorithms can be used to minimizes evacuations times during fire hazards. The efficiency of these algorithms mainly depends on the knowledge and familiarity to the physical layout of a building. Public safety in public buildings during fire hazards cannot be left depending on users' experience and familiarity to building or earlier taught fire drills only. The adding sensors to buildings helps feed evacuees with data that empowers them with the necessary real time evacuation information. Many lives that are lost yearly over fire incidents can be saved annually through the usage of intelligent evacuation methods within buildings.

Cloud-based real-time IoT systems seamlessly sends data online to cloud servers for dynamic processing and produces information that gives intelligence that informs them with safe evacuation details. Having lifesaving awareness of the state of crisis helps individuals make critical decisions and evacuation attempts or to get the necessary external support if needed. IoT based evacuation systems do no replace the but integrates and synchronizes multi-faceted rescue efforts. Emergency rescue workers and stakeholders like the fire brigade, police, building owners and buildings' occupants all share the feeds on critical information in its most correct form in the shortest possible time for safe evacuations in real time.

Traditional fire hazard management system largely relies on interpreting sensor signals that predominantly smoke sensors and fire detectors that are used to trigger alarms. Most of the fire hazard planning, designing and management techniques lacks correct real-time data for smarter and more calculated evacuations strategies. For example, the odourless, colourless and tasteless CO gas can easily claim evacuees lives whilst they are following standard evacuation procedures. Currently, fire and smoke sensors are located according to physical engineering designs that are void data sending and communication capabilities or have limited communication.

Homogeneous arrays of fire and smoke detectors are installed inside building to help send the warning or trigger semi-automated alarms or physically switched alarms when fire hazards happen. Alternatively, one can access the alarm switch by breaking the glass covers and pressing the buttons connected within un-intelligent electrical circuits. There is limited to no transfer of location information, time of fire incident, environmental air composition information and possible safe evacuation path in these processes.

The Internet of Things can build an electronic representation of the physical state of different things in our physical world, by measuring the physical quantities using appropriate sensors and send the information to any part of the world for monitoring and controlling. Data representing various environmental elements is processed to give out information which is when disseminated to inform vital decision support systems in real time.

CO poisoning related death issue is one example of a problem within a class of problems that occurs obviously due to lack of information as well as collaborative decision support and effort when fires occur. Fire crisis does not respect subject domains and contexts, we need concerted solutions that transcends different engineering and science domains. Smarter fire engineering systems need to emerge, that allows or helps evacuees make pre-emptive decisions to avoid and reduce loss of lives due to fires due to calculated human attacks or random God-events.

Exponential technological breakthroughs in modern computing systems, engineering and electronics has availed cheap and simple IoT technologies. These technologies can be harnessed and be instrumental in the designing and the implementation of smart and more efficient evacuation methods with minimal complexities. By and large, the potential of IoT to save carbon monoxide poisoning casualties and related deaths is imminent.

The remainder of our paper firstly discusses related work in the form of point to point evacuation algorithms namely; Dijkstra and its implementations in various systems in Section II, and then describes our implementation in Section III. Section IV describes how we evaluated our ambient air safety aware system and presents the results. Section V presents our conclusions and describes future work.

II. RELATED WORK

High mobile densities especially around metropolitan areas provides the enabling background for the use of smart Mobile Fire Evacuation Systems. Even without smart buildings we can deploy efficient evacuations systems that solely leverages on multiple sensors found on smartphones today. [1]

Alternatively, microcontrollers can be installed within buildings to integrate various sensor data that drives smart evacuation procedures. Smart city buildings are sensor-ready. The collection, processing and analysis of their indoor environment data for example evacuees real time location, number of occupants', their spatial distribution and the indoor hazard progression details in real-time data enlightens their real time evacuation designs. [4]

Modern evacuation algorithm like the Partitioned and Staged Evacuation Planning (PSEP) algorithm calculates not only the shortest evacuation path but optimises departure time for group within building ensuring that human behaviour driven swarming or congested during evacuation is avoided. More dynamic strategies like the Combined Staged Evacuation Strategy whose dynamic path planning involves waiting for ones' turn to be evacuated. This strategy of waiting in the original place when emergencies or hazards breaks out seems absurd, unnatural and unsafe. It can be practically applicable when local disasters such as an indoor fire occur within smart buildings since they generate more fire crisis information. [2]

Traditionally, Dijkstra Algorithm does not consider natural negative weights of edges. When water rushes inside a mining tunnel a once positively valued path will need to be revalued as negative since it can cause evacuation delays. To figure out optimal path after the mine water in rush a concept of equivalent path is used. This method takes the conversion formula of the equivalent path and the actual path, so traditional Dijkstra Algorithm got improved by providing a new method to calculate the optimal cost equivalent path. [10]

Evacuation Planning Methods(EPM) designs aims to create routes and schedules that can be used to evacuate people to safety when hazards happen. Poor planning and execution of methods can add more casualties. Evacuation designs need to be properly evaluated before being recommended for deployment. QueST, is an agent-based system that uses discrete event queuing network simulation, and STEERS, is an iterative routing algorithm that uses QueST to design and evaluate large scale evacuation strategies and plans considering total evacuation time and congestion or bottlenecks encountered in the evacuation stages. [17]

Usage of K-Shortest Paths algorithm to find the shortest path between two network nodes has been extensively examined in light of different application designs. Singular, decision making criterion is used to generate path decisions and these could be insufficient for real life analysis. Criterion such as cost, capacity, security, etc. needs to be considered for more informed decisions. This method converts the mono-criteria aspects for decision support to some more rich multi-criteria combinations. [18] [20]

A study was carried out to focus on the production of network traffic details that can be used to facilitate for the emergency evacuation from a city. An evacuation algorithm was generated by using two underlying models: firstly, to capture the optimal spatial location of safe shelters using the Wardrop's principle and secondly to handle real time decision during the evacuation processes. The high uncertainties and ever-changing variable that affects the transportation systems as a function of time during an emergency was studied. The result is a simulation algorithm that incorporates the shortest evacuation path with detailed traffic information. [21]

The N-Shortest Paths algorithm utilizes the Bidirectional Search Method(BSM) on Dijkstra's algorithm to minimise escape time and increase rescue efficiency when random coal mine floods happen. The weights of the edges are equivalent to the roadway lengths equivalence to simulate the working of the algorithm. A combination of the graph theory and the GIS theory is applied to establish the topological representation of the mine. Dijkstra's algorithm calculates the optimal path from the constructed undirected weighed graph. A resultant MATLAB graph simulation was

A Multi-Criteria Decision Making (MCDM) is a model that approaches evacuation problem by determining the best route. To achieved this, an Analytical Hierarchical Process (AHP) approaches the best route with the least cost as the optimal evacuation route from different alternative evacuation routes. The best route is chosen from alternatives as the one with the least cost in terms of time and distance and not safety. [23] Such pre-planned and calculated evacuation routes seem good prior to fire hazard events. During emergencies they cannot adapt responsively to real time evacuation dynamics. Pre-determined paths need to be re-configured to the type, intensity, or location of the emergency risk on time.

When addressing Outdoor evacuations', the effectiveness of evacuation route is limited by factors like path congestion, path disruptions, poor coordination mechanisms and the state of underlying transportation network. More recent solutions use hybrid simulation-optimisation methodologies that optimises integrated evacuation response strategies. The simulations involve demand staging and signal phasing and analyses evacuation efficiency from various combinations of evacuation parameters. [24]

RescueMe system thrives on exploiting smart phones' sensors, GPS user-positioning and Wi-Fi functionalities of user's mobile phones. Going further, it generates Augmented Reality, from personalized pedometers to create optimal exit path algorithms from studied individual's daily movement patterns. The system is grown on the assumption that each evacuee regularly occupies the building and most importantly, that they have smart phones equipped with the necessary sensors. [25] Comparably on the outdoor environment, Kaveh Shahabi and John P. Wilson created a tool that studies major works in evacuation routing to develop an algorithm that improves emergency evacuation management. [26]

Khyrina Airin Fariza Abu Samah et al designed an Intelligent Autonomous Evacuation Navigation (AEN) system. AEN solves evacuation path finding problems for buildings occupants' who are unfamiliar with a building when the need for emergency evacuation arises. AEN uses an independent evacuation navigation system that uses dynamic signage driven by sensor-based data to the shortest path towards the nearest exit. This design overly relies on building signage which can possibly be affected by fire out breaks that renders it totally inaccessible and so there is need to improve on this. [27]

Fire Evacuation Simulation

Consider an evacuee who has spatial familiarity or unfamiliarity at a random point, **S** inside a 3D building at the moment that a fire starts. Evacuee's natural yet random pathfinding behaviour to a safe exit will be a function of location **(S),** visited network intersection vertices **(V),** path/edges **(E),** distance of path **(D),** Un-visited network intersection vertices **(U),** paths' time cost **(C)** and CO concentration impedance **(I).**

The shortest open path for safe evacuations is a logical graph functional that depends on various parameters from the building given by

G = {V; I; D; E; S; U; C}

Where;

$V = \{ v_0 ; v_1; v_2; \ldots\ldots; v_n \}$	**V**isited edge of nodes
$I = \{ i_0 ; i_1; i_2; \ldots\ldots; i_n \}$	Set of CO impedances
$D = \{ d_0 ; d_1; d_2; \ldots\ldots; d_n \}$	Path lengths/distances-set
$E\ \{ e_0 ; e_1; e_2; \ldots\ldots; e_n \}$	Set of untraveled edges
$S = \{ s_0 ; s_1; s_2; \ldots\ldots; s_n \}$	Set of starting points
$U = \{ u_0 ; u_1; u_2; \ldots\ldots; u_n \}$	**U**n-visited edge of nodes
$C = \{ c_0 ; c_1; c_2; \ldots\ldots; c_n \}$	Cost(safety) from **U**s to **V**s

```
INITIALISATION:
U = {u0; u1; u2; .......; un} // Un-visited first nodes or starting point of each edge
S = { }                        // Set of selected nodes or visited node
SELECT starting point
FROM

S = { s0 ; s1; s2; .......; sn }   //Set of possible starting points
FOR each node (u, v) ∈ E (i) DO
IF v adjacent to node u
    W(v) > w(u) + w (u, v) THEN W(v): = d(u) + w (u, v) AND
    Visited Node (v): = u // u is now the current visited node

    W = { w0 ; w1; w2; .; wn }      //Weight of direct paths to Vs
    w = { w0 ; w1; w2; ...; wn }    //weight between edges Us to Vs
    THEN W(v) = w (ui; vj)

    ELSE W(v) = ∞                   // Node not reachable
  LOOP
  FIND
      v not in U or V: W(v) is a minimum distance
  ADD v to V
  UPDATE W(v) for all u adjacent to v and not in U:
    W(v) = minimum ((W(u), W(v)) + w (u, v))
  UPDATE w (u, v) as either old total weight to v or ∞
  UPDATE shortest path to u plus weight from u to v
  UNTIL
  All nodes in U are in the visited nodes set
  E ≠ {}
```

III. IMPLEMENTATION

We implement our algorithm design for ambient air safety aware autonomous evacuation algorithm improving on MQTT mobile application subscribed to by buildings occupants.

We considered our graph as a mathematical function collecting vertices/nodes which are (un)directed connected by edges labelled by weight. In order to evacuate a building when a fire breaks out, an evacuee start at any point, s_i. From s_i he needs to make a decision on which path to take. Safe walkability of an open path is subject to factors like invisible impedances(i_i) e.g. CO gas and visible impedances like smoke, high temperatures, blockages etc. as well as the distance(d_i) of the chosen edge' size of the path, number of un travelled(u_i), total number of edges(e_i), the starting point(s_i), number of turns as well as safety cost(c_i) to traverse each edge.

This essentially defines a high dimensional space problem in which we need to consider all parameters(x_n), that affects safety of a route and consider their corresponding variations and weight(w_n), towards making the path safe and walkable in real time. Without this, a path can never be considered as fully safe. So, we need physical arrays of homogeneous-sensor-sets that are lined up along all the possible paths to push data to a cloud based server for real time monitoring all the time.

It is hard to impossible to have x_n different parameters and sensors randomly aligned for optimal or safest evacuation values under fire conditions. This renders path selection decision a complex NP problem because of the rapid changing data space and we also need to reinforce the route to safety that causes no computation based delays and during emergency scenarios.

1. By conceptualising each sensor set as a singular edge weight with a unique combined-sensor-sum weight value.
   Edge **Weight** = $\sum_0^n \textit{Sensor Set}$
2. Limiting the number of parameters(x_n), that affects safety of a route to ones with sensor based parameters only:**G = (V; W)**
   Where; W = $\sum_0^n i$ and **v** represents vertices
3. Setting combined-sensor-sum weight threshold value that informs path decision making logic.
4. Ensuring that no sensor set coincides with the physical building nodes (add sensor sets as edges only)

G = (V, E, W) where V, represents the collection of nodes.
E, represents the collection of edges.
W, weight of a safety risk

Edge is representing the corresponding nodes **(u, v)**.

G (V, E, W) is a set of subgraphs, **G = {*G*1, *G*2, *G*3, …*G*n}.** This represents ***n*** partitions of G. Where, ***G*1 (v1, *e*1, *w*1), *G*2(v2, *e*2, *w*2), *G*3 (v3, *e*3, *w*3), …, *G*n (vn, *e*n, *w*n)**

These subgraphs are connected maximally, if every node within the undirected graph is connected such that there exists a path from each node that can be used to reach every other node.

Given a particular starting vertex(s_i) or starting point called the **source**, we can compute the safest path from source to any other exit or sinking vertices by choosing a series of adjacent edges with the minimum weights.

For any given G there exist i adjacent to j for the edge formed by the node pairs *(i, j).* We can define a set of node j adjacent to node i,

Adjacent(i)= {j | ((i; j) Є **V** or **(**j, i) Є **V**) and (i, j Є **V**)},

Where $i \in V$ and $j \in V$, for every $1 \leq i, j \leq n$ and $i \neq j$.

Safest path from(s_i) to safe exit (V_{Exit})is the collection of edges(V's) whose total weight of risk is the smallest compared to others.

Prototype Implementation of Safety Aware (based on Dijkstra's Shortest Open Path)

- **Establish logical network based on sensors installed along building's pathways**
  - Each sensor publishes its reading using MQTT protocol
  - Where pathway weight equal time cost between connected nodes
  - If sensor reading is acceptable or safe

Compare path weights

  - Else set pathway weight to ∞
  - Since they can result in evacuation delay
  - Set delay value pathways to ∞
- **Compute least cost paths from Source node to Destination(Exit) node**
  - Point LED signage green towards the safest path
  - Point LED signage red towards the un-safe path
- **Continuous Iterations: Real time weight updates**
- **Display safe path on the cloud**
  - Mobile cloud application
  - Application displays evacuation pathway in black with sensor readings

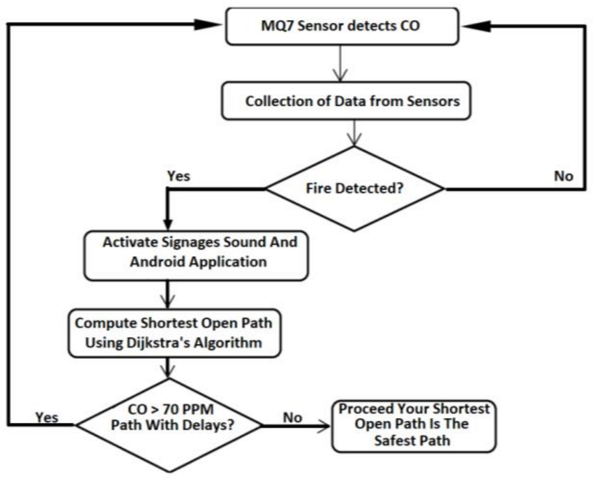

Figure 1: CO Safety Aware Autonomous Evacuation System.

The algorithm design implements safety aware autonomous evacuation System to simplify the wayfinding processes to occupants when fire breaks out. A cloud-based system sends real time updates and alerts of indoor environmental-CO levels. MQ-7 sensor readings are used to establish Air Quality Index (AQI) before broadcasting on the mobile cloud of stakeholders using Message Queuing Telemetry Transport (MQTT) protocol. All IoT devices and end-users communicate via Esp8266 Wi-Fi module (broker). Paths with impendences like very high CO levels are published to all subscribers as hazardous and with reversed signage. Transport layer security Protocol secures the data in transit between sensors and Thingspeak server. Deployed MQ7 sensors collaborates with each other via the NodeMCU-12E broker to determine the path to safety. LEDs are deployed over the possible paths to control and sends readings to a cloud based server. The safe path is displayed on the phone application and the physically as LED signage inside building that enforces optimized evacuation parameters.

IV –RESULTS

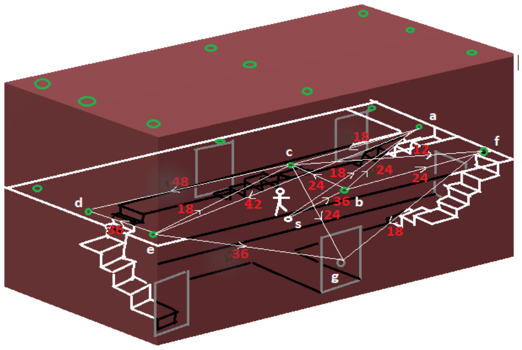

Figure 2: Building Under Normal Conditions

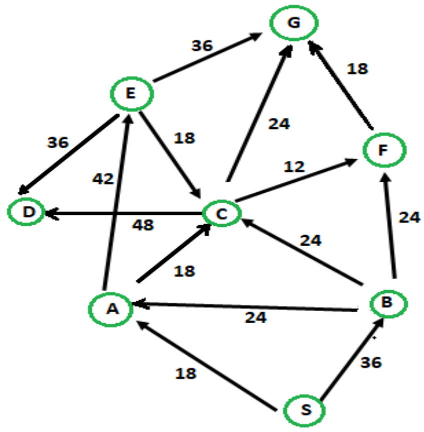

Figure 3: Graph Under Normal Conditions

Table 1: SHORTEST OPEN PATH IN NORMAL CONDITIONS

s	A	B	C	D	E	F	G		
0	∞	∞	∞	∞	∞	∞	∞	S→s = 0	Select, **s**
	18	36	∞	∞	∞	∞	∞	s→A = 18 s→B = 36	Select, **A**
		∞	36	∞	60	∞	∞	s→ A→ E= 60 s→ A→ C = 36	Select, **C**
				84		48	60	s→ A→ C→ G= 60 s→ A→ C→ F→ G = 66	Select, **G**

The shortest open path is s→ A→ C→ G= 60

This is obviously not a safe path if we look at edges from **s,** to nodes **a** and **c** which are under more hazardous fire conditions. Negative weight sign indicates likely delay of the evacuee from escaping if there is no precaution taken during the escaping process.

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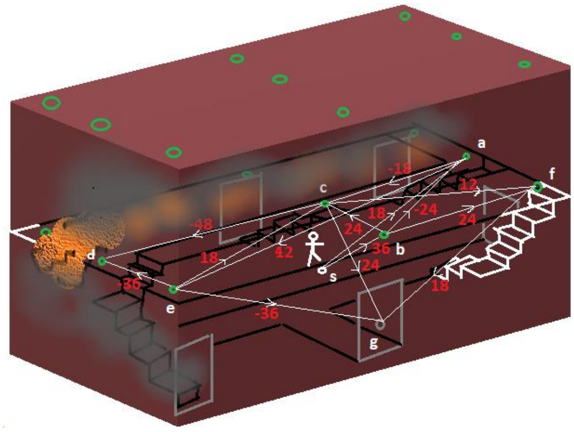


Figure 4: Building Under Hazardous Conditions

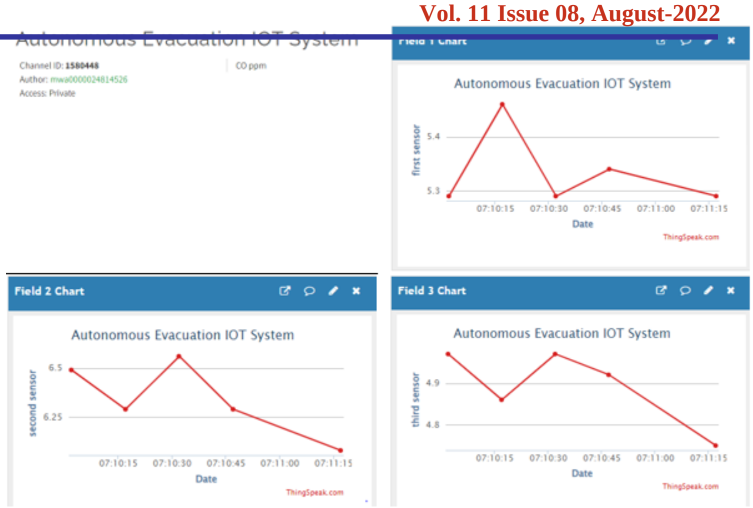


Figure 6: MATLAB – Homogeneous-Connected-Sensor readings

Table 2: Safest Open Path Under Hazardous Conditions

G = {V; W; I}
Where; V represents vertices
W represents weight according to time cost
I represent impedances which makes evacuee turn back causing delays

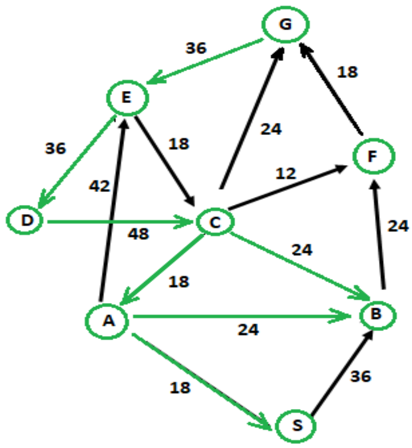


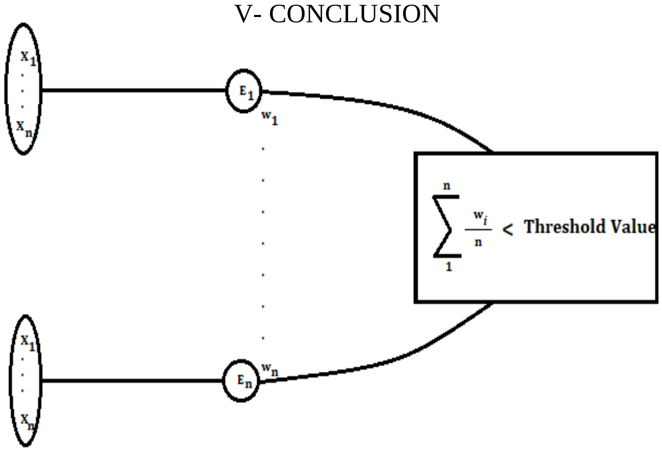
Figure 5: Graph Under Hazardous Conditions

Table 2: SAFEST OPEN PATH UNDER HAZARDOUS CONDITIONS

s	A	B	C	D	E	F	G		
0	∞	∞	∞	∞	∞	∞	∞	S→s = 0	Select, s
	∞	36	∞	∞	∞	∞	∞	s→B = 36	Select, A
		∞	∞	∞	∞	24	∞	s→ B→ F= 60	Select, C
			∞	∞	∞	∞	18	s→ B→ F→ G= 78	Select, G

The previously calculated shortest open path is s→ A→ C→ G= 60 has a minimum time cost but obviously not a safe path considering the impedances at node, **a** and **c.** The safest path is s→ B→ F→ G= 78.

V- CONCLUSION



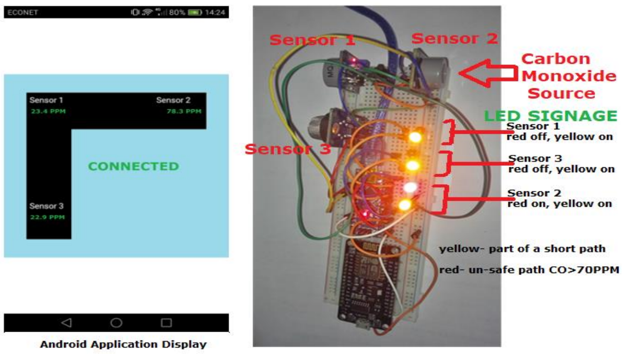
The average readings of each sensor set is calculated as,

$$\sum_1^n \frac{w}{n} = \bar{w}.$$

When this value is less than the threshold value(T), it represents a desirable, averagely safe path ahead which is displayed as the black path or connected path in the diagram below. From the homogeneous set of CO sensors used for our proto-type, we have a connected path to safety.

$$\bar{w} = \sum_1^n \frac{w}{n} = \frac{23.4 + 78.3 + 22.9}{3} = \mathbf{41.5}\ \text{ppm}$$

This is a seemingly good value since it is less than 70 ppm which is the safety threshold for indoor CO concentrations. Un-expectedly, safety can never be based on averages. Sensor 2 has a reading above 70 ppm and the LED signage has the red light on and an evacuee cannot proceed without taking the necessary precautions.



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Mathematical Function for safe and walkable CO levels

Fig 7: Android Application (left) and Prototype(right)

CO Safety Function = 1

70 - W_i >0, Not safe. Proceed with precautions.

5.1 Conclusion

Ambient Air Safety Aware Autonomous Evacuation system generates not only the shortest connected path from source to destination but enforces safety along the path through signage. The worst case scenario would be a totally shut blockage of paths where there is no connected path to safety. There is need to work on making our building smarter, for faster data based evacuations and to avail equipment within buildings that enables evacuees to autonomously evacuate whilst maximising fire safety.

5.2 Recommendations

This study was considered the use of LED signage as the single connected pathway enforcement from source or starting point to the exit. This is not ideal for some situation. We recommend the usage of audio or other sensory enforcement and further evacuation considerations using multiple source or starting point for evacuation in order to extract more understanding on how to evacuate more people simultaneously.

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